SCIENCE FOR GLASS PRODUCTION

CAUSES OF SURFACE DAMAGE OF THERMALLY POLISHED GLASS IN PRODUCTION

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The causes and conditions of formation of incipient cracks in the course of production of thermally polished glass and further evolution and behavior of cracks in service are considered.

The Si – O chemical bond, which is the foundation of the silicon-oxygen tetrahedron and the basis for glass structure, is very strong. Consequently, one can expect high strength from glass as well. Griffiths was one of the first to estimate the theoretical strength of glass. Based on the dependence of the strength of a glass filament on its diameter, Griffiths extrapolated this dependence to the diameter of a molecular-size filament and came up with the strength of 11,120 MPa [1]. In practice the strength of glass is less than 1% of the theoretical value. The cause is the damage to glass caused in the course of production, which is determined by the emergence of micro- and macrocracks.

The purpose of the present study is to determine the mechanism and the terms of emergence of the most dangerous cracks in the course of production and service of thermally polished glass.

The investigated glass samples were 3, 4, 5, 6, and 8 mm thick and were manufactured at a speed of 300, 250, 200, 160, and 100 m/h. Longitudinal glass samples of size 1700 × 400 mm were cut out of a glass band, inspected, and the detected cracks were photographed in polarized light using an MP-7 microscope and a Zenith-3M photo camera with elongating rings. The photo camera in this case also functions as a microscope with magnification from ×10 to ×100. Polarized light was obtained using a PKS-125 polarimeter. The intercrossed polarizer and analyzer produce a "dark field" in which only the glass sites with increased stresses are glowing. It should be noted that in addition to the microcrack itself, the stressed fields around it, whose magnitude is two orders greater than the crack, glow as well, which substantially facilitates the search for microcracks and their study. At first the glass surface is inspected at low magnification and the color field produced by the crack is identified. The glass area containing the crack is marked by a pencil and cut out. The cut out samples are 150 × 200 mm. After that the magnification is increased to ×100 and the crack is investigated.

In using the given production technology, the glass band is first molded on the surface of tin melt at a temperature of 600 – 610°C and then conveyed onto the roller conveyor and sent into the annealing furnace. The bottom part of the glass band moving over the melt captures tin oxides. When the glass contacts the roller conveyor shaft, the oxides stick to the hot surface of the shafts, and a bulge (riveting) is formed on the shaft surface, which with the next to the last revolution is pressed into the bottom surface of the glass. In this way an indentation is formed on the plastic glass. Three indentations were identified on a glass strip 1700 mm long, and the distance between them was 567 and 569 mm, which agrees well with the shaft diameter equal to 180 mm.

Thirty to fifty minutes later, a microcrack emerges in the corner of the plastic indentation, which evolves spasmodically and after two years of observation attains the length of over 2 mm.

Within the temperature range of the glass band arriving at the conveyor shafts, the reaction of glass to the bulge pressing can be either elastic (reversible) with formation of elastic cracks, or inelastic (irreversible) with formation of plastic indentations.

The nature of reaction is determined by the speed of pressing and the speed of relaxation of stresses arising in glass as the result of this action. The level of stresses in terms

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of their continuous relaxation under isothermal conditions can be found from the equation

$$\sigma_t / \sigma_0 = \exp[-(t/t_r)]^{0.5},$$

where σ_0 are the elastic stresses arising in elastic (cold) glass; σ_t are the elastic stresses in the same conditions of pressing which arise in viscoelastic (hot) glass; t is the duration of pressing the bulge into the glass; t_r is the time of stress relaxation in the glass.

Thus, the nature of the interaction between the shaft and the glass is determined by the ratio between t and t_r.

The relaxation time t_r is found from the empirical dependence

$$\log t_r = \log \eta - 11.5,$$

and the viscosity η is found from the relationship

$$\log \eta = -2.78 + 5574/(T - 474),$$

where T is the temperature.

The time of pressing the bulge into glass t depends on the bulge height h, the shaft radius R, and the rate of glass band production v_b and it is calculated according to the scheme in Fig. 1. The calculation was performed for actually detected rivetings on shafts with a height of 0.5, 1.0, and 1.5 mm. For this calculation it is necessary to know the arc length l_{AC}. Since $R \gg h$, we take $l_{AC} = l_{AB}$. Then the sought for time is equal to

$$t = l_{AB} / v_b;$$

$$l_{AC} = l_{AB} = \text{arc} \sin \alpha;$$

$$\sin \alpha = \sqrt{1 - \cos^2 \alpha} = \sqrt{1 - \left(\frac{R}{R+h}\right)^2}.$$

With the bulge height 1.5 mm and the speed of glass sheet movement varying from 100 to 300 m/h, the time of pressing decreases from 0.56 to 0.19 sec.

The parameters t and t_r for different glass temperatures and different rates of glass production were calculated using the above listed relationships. The obtained data were introduced into the first of the above equations. The calculation results are shown in Fig. 2. It can be seen that the speed of the roller conveyor affects the relaxation processes in glass, whereas an increase in the speed from 100 to 300 m/h produces a 2.6-fold increase in the share of elastic stresses at a temperature of 620°C, 1.47-fold increase at a temperature of 600°C, and at a temperature of 570°C the share of elastic stresses increases only by 10%.

Thus, with increasing speed of the roller conveyor, the probability of elastic interaction increases and the probability of formation of plastic indentations decreases.

The temperature of glass has an even greater effect on the relaxation process. As the temperature varies from 570 to 620°C within the same range of the roller conveyor speed, the share of plastic deformation grows from 0.2 to 0.85, i.e., more than 4 times. The probability of indentations is espe-
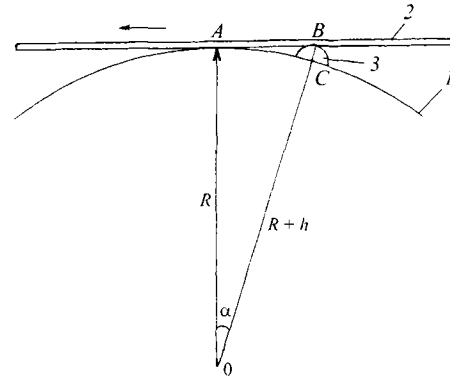

Fig. 1. Diagram for calculating the time the bulge is pressed into the glass: 1) roller conveyor shaft; 2) glass band; 3) the bulge on the shaft.
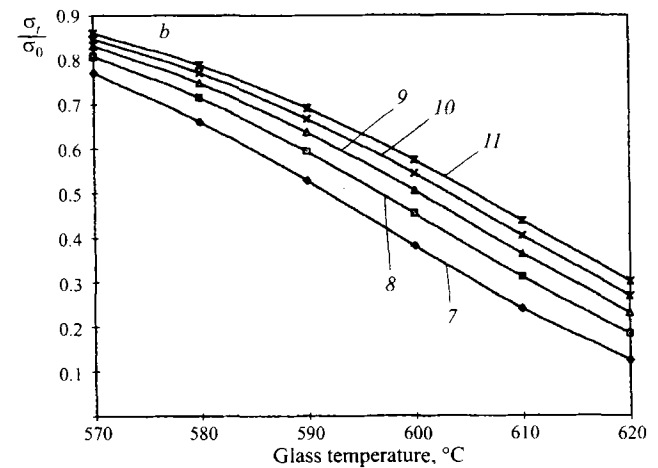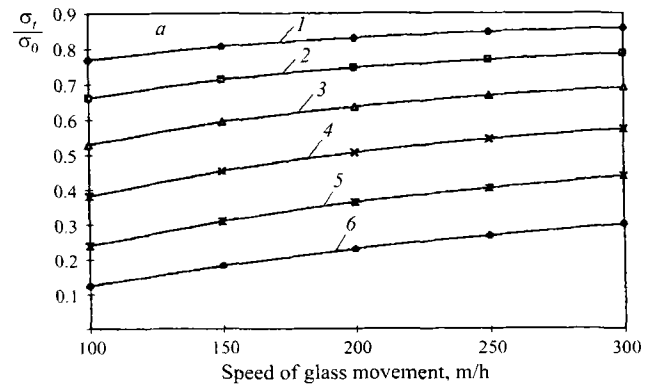

Fig. 2. Ratio between the elastic and plastic glass deformation depending on the speed of glass movement on the roller conveyor (a) and the glass temperature (b): $1, 2, 3, 4, 5, 6$) 570, 580, 590, 600, 610, and 620°C, respectively; $7, 8, 9, 10, 11$) 100, 150, 200, 250, and 300 m/h, respectively.

cially high in the glass produced at a low speed, namely, the glass 8 and 10 mm thick, since in this case the share of plastic deformation grows up to 0.9. Moreover, the unit pressure of this glass, which determines the force of the bulge indentation into the glass, is also the highest in this case. This accounts for the fact that plastic indentations are most often found on glass 8 and 10 mm thick.

Elastic interaction is manifested in the emergence of microcracks, chafes, and notches (Griffiths cracks) in the glass, which can be seen at great magnification after special treatment of the glass with hydrofluoric acid. The plastic indentations can be seen by the naked eye.

It is commonly accepted that the strength of glass decreases due to the existence of the Griffiths cracks, whereas plastic indentations mostly impair the optical properties of glass and do not affect its strength. In practice it was found that under certain conditions plastic indentations can be a cause of glass fracture. The main condition of the formation of destructive cracks is a certain ratio between the elastic and the plastic components. Based on the calculation, this ratio is 0.25 : 0.75 for the elastic and the plastic interaction, respectively.

The optimum conditions for the formation of destructive cracks are developed within the temperature range of 610 – 620°C and a rate of production of 100 – 150 m/h. Thus, the plastic deformation stage in glass is necessary for the emergence of the most dangerous defects.

The same regularities are found in cutting elastic (cold) glass with a standard hard-alloy roller. The roller load develops compressive stress in the glass. The level of the stress is sufficient to produce a local compaction in the glass due to its plasticity (irreversible flow). As the load is removed, the stress does not disappear due to the irreversible deformation but changes sign: an intense tensile stress arises. The stress field is nonuniform and has preferential directions.

Three directions were identified in cold glass: one deep into the glass and two lateral directions each at 45° to the first one. Accordingly, three cracks emerge [2]. Typically, the cracks do not arise at the moment the roller is pressed in the glass, but some time after the roller passes. The same regularity is preserved in pressing the roller into hot glass. The crack seed originates in the corner of a plastic indentation 20 – 30 min after the pressing. The seed is a capillary with an opening. Due to the capillary condensation, atmospheric moisture gets to the crack apex and the crack starts spasmodically growing. The initial growth of the crack occurs at a relative air humidity equal to 30 – 40%. After the crack attains a length of 1.5 mm, further increase is observed only at 100% air humidity (rain or fog). The crack propagates both along the glass surface and deep into glass. Branching of the crack is observed. After 3 – 4 years of service such glass can break under the effect of an ordinary wind load.

REFERENCES

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